2nd International Conference on Advances in Experimental Structural Engineering
Tongji Univ., Shanghai 200092, China
December 4-6, 2007

EXPERIMENTAL TESTS ON MASONRY STRUCTURES: FROM THE SIMPLEST IN-SITU TEST TO COMPLEX LAB TEST SETUPS

Alexandre A. Costa[1], António Arêde[2] and Aníbal Costa[3]

[1] *Faculty of Engineering of the University of Porto, Portugal, aacosta@fe.up.pt*
[2] *Faculty of Engineering of the University of Porto, Portugal, aarede@fe.up.pt*
[3] *Departamento de Engenharia Civil, University of Aveiro, Portugal, agc@ua.pt*

Abstract

This paper presents different experimental test techniques used to assess the behavior of different masonry structures. The test setups presented can be considered from the simplest one for in-situ use, to more complex ones used in laboratory conditions. Some examples are presented as used to assess the in-plane and out-of-plane performance of masonry walls subjected to loads using simple in-situ or complex laboratory setups. In particular, an experimental test for behavior assessment of a masonry arch bridge is referred as an example of a simple test methodology with complex instrumentation. Finally, some comments are included regarding the efficiency of simple test schemes when compared to more complex and elaborated test setups as well as the applicability of the later to in-situ or laboratory conditions regarding costs, time and the need for their use.

Keywords: Masonry walls, Arch bridge, Experimental, In-situ tests, Laboratory tests, Monitoring

1. Introduction

Experimental tests are a major issue on structural engineering due to the relevant outcome for design and assessment purposes. Several different test types can be performed on elements/structures, such as material characterization, fatigue, cyclic behavior or even seismic performance assessment of complete structures.

However requirements to perform complex tests are not always available mainly due to technical issues and costs associated with the involved procedures. Hence, engineered solutions can be arranged in order to obtain equivalent experimental results using alternatives to the desired test setups.

In this context, different test procedures to assess the behavior of elements and structures will be briefly presented based on experimental activities already carried out with different load conditions, control procedures and monitoring techniques; more relevance is given to the most innovative solutions.

2. Experimental Tests on Masonry Panels

Testing of masonry panels is a key issue to allow predicting their performance under seismic excitations, particularly because under simple quasi-static loading it is possible to estimate the cyclic response envelope. Actually, this can be done by recourse to experimental tests on masonry panels subjected to vertical forces (simulating the mass of a structure above it) and a horizontal load applied at a given height in order to simulate the inertial excitation due to an earthquake action. Different ways can be adopted to apply these loads, namely monotonic, cyclic and earthquake simulation as detailed in Tomazevic [1] and Costa [2].

Additionally, reproducing adequate restrain conditions is another issue playing a major role in this type of experimental tests. While it is possible to simulate a cantilever response of a masonry pier or a fixed-ended condition on a masonry panel, as mentioned by Costa [2], it is also clear that *in-situ* boundary conditions are very hard to reproduce in laboratory and, therefore, the best way definitely consists on playing with *in-situ* testing.

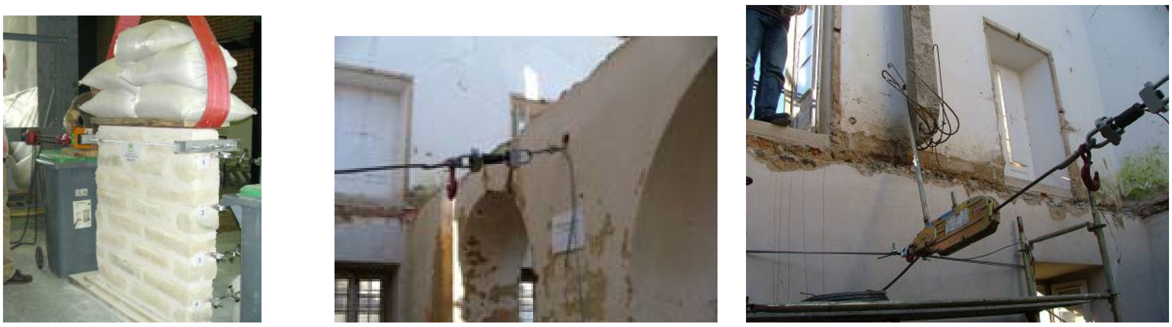
2.1. In-plane Behaviour

In order to assess the lateral capacity of masonry piers with a simple test setup, a shear load should be applied on the specimen. However this shear load can be applied in several different ways either in the laboratory or *in-situ*.

The first case presented herein refers to a test setup recently used at the University of Aveiro (Portugal), consisting of a very simple system shown in Fig. 1 a), in which a simple load-handling mechanism attached to a steel cable was used to impose lateral forces by cyclic varying the cable tension but without reversals. The horizontal force was monitored using a digital dynamometer, whereas the vertical force was applied at the top resorting to dead load using controlled weight cement bags. Displacements were controlled using mechanical dial gauges rather than electronic devices.

This test setup, in what concerns horizontal loading, was inspired on a process used for the profile correction recently carried out on a large masonry wall of the Tibães Monastery (http://www.mosteirodetibaes.org/) near Braga, Portugal, that was monitored by the Laboratory of Earthquake and Structural Engineering (LESE) of the Faculty of Engineering of University of Porto (FEUP). The same loading system was adopted there, though with more powerful manual devices (*tirefort*) and the idea was subsequently used in the assessment of the in/out-of-plane capacity of a masonry arch pier in the Aveiro Museum (Fig. 1 b)), taking advantage of a stiffer wall to act as "reaction wall" (see Fig. 1 c)).

From Fig. 1 it is clear that this system is a low cost and very simple test setup that can be used either in the lab or *in-situ*, adopting any kind of monitoring devices.



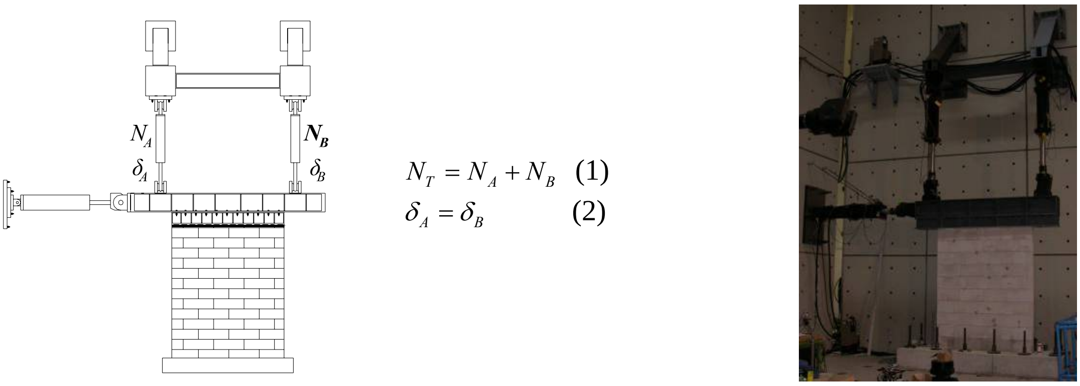
(a) **(b)** **(c)**

Figure 1: Simple setup for in-plane testing of masonry panels: (a) at lab facilities, (b) and (c) *in-situ*.

Typical experimental laboratory tests on masonry panels can be considered at an intermediate level of complexity because simplified test setup apparatus and simple PID controllers are often used. Results obtained from such tests are very helpful on studying carefully masonry elements and for developing numerical behavior models, mainly because the specimens can be fully instrumented and precisely displacement-controlled using hydraulic actuators in laboratory controlled conditions. An example of such a test setup is shown in Fig. 2 referring to the system currently used at LESE-FEUP for testing masonry walls in a typical cantilever test setup (as explained by Costa [2]).

Another case, referring to the experimental test setup currently in use at the EUCENTRE facilities (Pavia, Italy) is presented in Fig. 3. The system was designed to assess the in-plane behavior of masonry panels under double bending condition [2] and it can be considered a complex test setup because it makes use of a mixed force/displacement controller on the two vertical actuators to apply the vertical load and to ensure the horizontality of the top beam. The test may be considered stable and valid if the conditions (1) and (2) expressed in Fig. 3 a) are met, where N_T is the total axial force and (N_A , δ_A) and (N_B , δ_B) refer to the forces and displacements on actuators A and B, respectively. Despite the complexity of the test setup controller, this is a very simple apparatus allowing any kind of measurement devices, fast operations between experiments, clear view of the specimen and, last but not the least, safe even with the collapse of the specimen [2].

Figure 2: Test setup currently in use at FEUP (Faculty of Engineering of the University of Porto).



(a) **(b)**

Figure 3: Complex test setup at EUCENTRE, Pavia, Italy: (a) scheme, (b) testing a masonry panel [2].

2.2. Out-of-plane Behaviour

The out-of-plane motions of masonry walls during earthquake are commonly associated with partial or fully collapse of masonry panels or even buildings, as recently observed in Bam 2003 or Pakistan 2005 earthquakes. Indeed, experimental tests general related to this topic are essentially based on shaking table tests, airbag tests (Griffith [3]) and waterbag tests (Mosallam [4]), aiming at simulating the panel distributed load due to seismic excitation. However, some experimental tests with concentrated loads on the masonry panel have been also performed, as reported in Milani et al. [5]. Despite the fact that all these experimental tests were successfully done and implemented in laboratory conditions, they are not easy to be done *in-situ* due to the test nature and because reaction structures or shaking tables are required.

Bearing this in mind, and also the need for gathering realistic information of the behavior of structures as they exist, two different test setups were already used *in-situ* by the authors in order to simulate the seismic action on masonry panels of existing constructions, as described below.

The first setup presented in this paragraph refers to *in-situ* tests carried out in the Faial island, Azores, Portugal, after the Azores 1998 earthquake, during an experimental test campaign by Costa [6]. The test setup consisted on two steel buckets that could be filled with sand and able to vibrate freely, suspended by a steel cable to an auxiliary steel bar structure attached to the wall specimen (Fig. 4).

(a) (b) (c) (d)

Figure 4: *In-situ* test setup used by Costa [6]: (a) site 1, (b) site 2, (c) site 3, (d) monitoring devices.

With this system, horizontal out-of-plane forces were imposed to the wall by applying vertical loads in the buckets. In addition, load cycling was also made possible by means of forced oscillation of the bucket and by playing with the phase angle of two bucket cyclic motion, one in each side of the wall. Fig. 5 thus presents the force plot from the two steel buckets oscillating with a small phase angle.

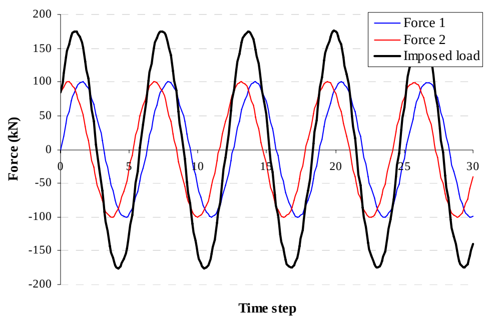


Figure 5: Possible imposed loads by Costa [6] test setup.

Associated with this simple test setup, also simple monitoring devices were used for quick and easy installation. Despite the adoption of simple mechanical dial gauges to obtain the out-of-plane displacements as shown in Fig. 4 d), it is apparent that any other type of other transducers could have been used in this test setup. However, it is also clear that this test setup is very limited regarding the load itself because it is “force controlled” with a limited load pattern.

Recently, an experimental test campaign was performed in Azores with more sophisticated test setup and monitoring devices. Indeed a portable and powerful test scheme was developed (as stated by Arede et al. [7] and Costa et al. [8]) where hydraulic jacks were used to apply the desired loads and draw wire position transducers (DWPT) were selected to monitor out-of-plane movements, with a range of 150-625mm and a linearity of ±0.1% of full scale (WayCon™). These instruments were controlled and monitored using a laptop and two small USB devices (National Instruments™ USB-6210 and USB-6211 with a maximum sample rate of 250 ksamples/sec), which allows to handle a total of 16 differential input channels (or 32 non-reference single ended input channels), two differential output channels and 5 digital channels. Finally the applied force was monitored using a load cell on the tip of one hydraulic jack.

All these instruments (data acquisition and control devices) were controlled by a computer code developed at LESE-FEUP allowing real-time control and acquisition based on the LabVIEW software. Fig. 6 presents all the equipment used to perform such tests.

(a) (b) (c)

Figure 6: Equipment used by Arêde et al. [7]: (a) acquisition and control devices, (b) hydraulic power unit and actuators, (c) DWPTs.

In this new experimental test setup two parallel walls were tested simultaneously, based on an action-reaction scheme. Indeed the hydraulic jacks were placed in between and connected to these walls at the roof/floor level in order to simulate the floor/roof effect and the masonry inertial forces, as it is represented in Fig. 7.

(a) (b) (c) (d)

Figure 7: Experimental test setup: (a) reproduced effect, (b) *in-situ* plan view, (c) local 1 (d) local 2.

Using this test setup it is possible to study simultaneously the out-of-plane behaviour of two walls in the same experimental test, monitoring both walls at the same time. This means that it is possible to go up to the collapse of the weakest wall in this *in-situ* experimental test setup because the stiffer one acts as "reaction wall" up to the end of the test.

3. Masonry Bridge Case

The structural behaviour of stone masonry bridges is still a challenging and pertinent topic of research, although it typically refers to old structures. The very fact that a large number of such constructions exist, in Portugal as in many other countries, under service conditions for which they were not designed, increases the problem relevance [9].

The following case study refers to the new stone masonry bridge in Vila Fria - Portugal, over the Vizela River, recently built according to traditional techniques of masonry construction to replace an old and very deficient passage (Fig. 8).

The bridge is 6 m wide and has a total span of 60 m, distributed by five stone arches of 4.8 m to 6.0 m long and two abutments. The main structural elements, namely arches, piers and spandrel walls are fully made of stone masonry brickwork, whereas the bridge interior is made of filling material composed by a selected *tout-venant*.

3.1 Instrumentation and Data Acquisition

By taking profit of the construction process a large instrumentation network was installed in the bridge, including both electrical type and fibre optic based sensors, the later particularly relying on fibre Bragg gratings [10].

(a) (b)

Figure 8: The Vila Fria bridge: (a) old passage and (b) new stone masonry bridge.

Strain in stone blocks is measured in 48 points by electrical and optical strain gauges (Fig. 9); since this type of structure has very low stress level in the linear elastic domain, the strain measures give directly an indication of the stresses installed.

(a) (b) (c)

Figure 9: Strain gauge layout: (a) downstream façade alignment (similar for the central alignment), (b) electrical strain gauge in the respective stone slot and (c) gauge location in the extrados.

Pressure distribution in a selected region is monitored by 7 total electrical pressure cells [11] as usually adopted in geotechnical works (Fig. 10). Vertical movements are obtained using 16 ultra-low differential electrical pressure sensors from Honeywell with an appropriate silicone oil to measure differential displacements between a series of points along the bridge deck. Relative opening/closing and slip displacements in joints between blocks, as well as relative displacements between spandrel walls are monitored by means of 53 displacement transducers based on fibre optic sensors; the same technology has been adopted for temperature measurement (28 sensors).

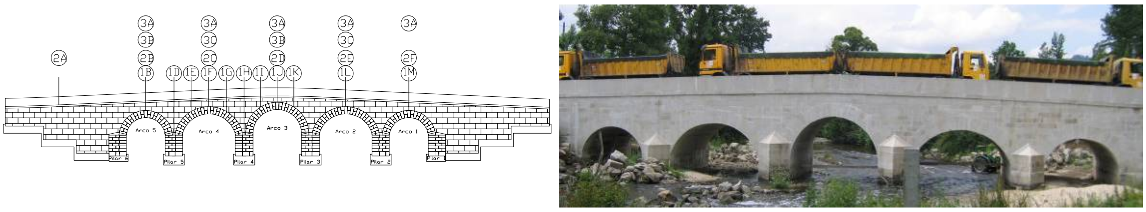
(a) (b) (c)

Figure 10: Total pressure cells: (a) location, (b) circular cell (pier-infill) and (c) half-moon cell (inside stone blocks).

Data of all the sensors are collected by appropriate acquisition systems, namely one BraggMeter measurement unit containing an optical switch from FiberSensing and one Compact Fieldpoint acquisition unit from National Instruments. Both equipments are connected by TCP/IP to a router allowing wireless data transmission by GPRS/UTMS to a remote server at FEUP where monitoring results are collected in a specifically designed database and accessible through an internet site (http://remotelese.fe.up.pt/). The whole monitoring system is described in detail in [12] and [13].

3.2 Load Test

After completion of all the activities related to instrumentation, calibration and whole system testing, the load test on the bridge was carried out using four trucks loaded to their maximum capacity around 39 ton (40% for the two front axles and 60% for the two rear axles). Three vehicle arrangements were adopted to obtain the most unfavourable structural effects [13]. In order to obtain a more concentrated load, the arrangement 1 consisted in just one pair of side-by-side trucks in twelve stopping positions along the whole bridge length defined by the middle position of the two rear axles. Fig. 11 shows the stopping positions for the trucks along the bridge for the three arrangements (1A to 1M, for the first; 2A to 2F for the second; 3A to 3C for the third), as well as a photo of one test stage (3A, with trucks all over the full length of bridge arches).



(a) **(b)**

Figure 11: Load test: (a) truck stopping positions and (b) truck arrangement for position 3A.

The arrangement 1 was found to produce the most unfavourable effects. The most expressive results refer to the pressure values obtained from pressure cell readings that can be seen in Fig. 12: note the most unfavourable situation for position 1F right above the arch crown, as expected. Vertical alignments of these plots correspond to the several stopping positions and are identified in Fig. 12. Positive values refer to increase of compression that are detected in the arch 4, the most instrumented one and likely to exhibit more pronounced effects. A general overview of the observed behaviour confirms the large stiffness of the bridge that is consistent with the very low deformations recorded: 0.31mm for the vertical deflection at the crown of arch 4 and joint closure of 0.16mm in the same zone.

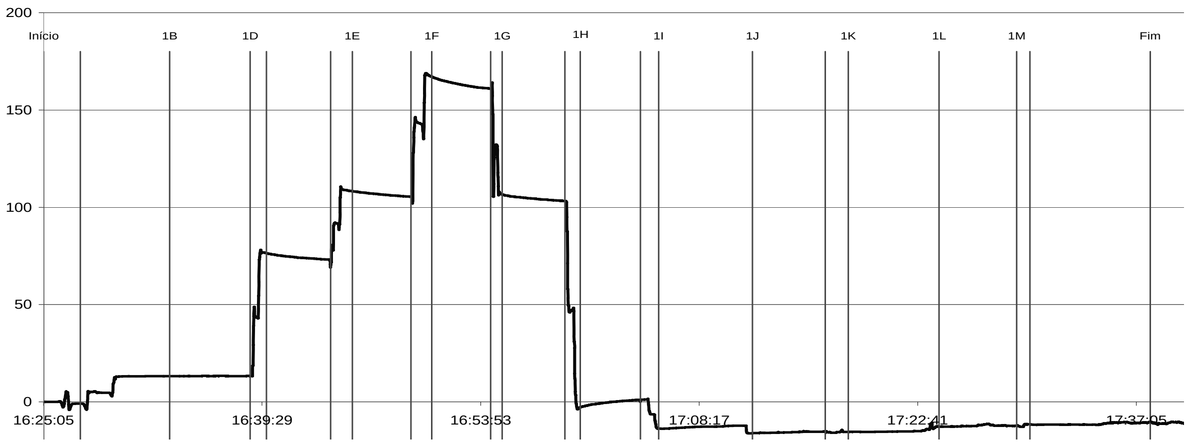


Figure 12: Load test results for arch 4 and load arrangement 1 - Stress evolution (kPa) in load cell C7, for all positions of the first vehicle arrangement.

Long term monitoring results are already available since May 2006, although not yet processed and analysed; they are expected to provide information regarding the influence of temperature on the sensors' response.

At the same time several numerical simulations were performed to simulate the response of the load test, using the general purpose computer code CAST3M [14] and finite element modelling strategy as reported in [12] and [15].

4. Conclusions

The significance of *in-situ* tests was remarked in this work due to their own characteristics and outcome. They are really important to study elements/structures under their natural conditions, as vertical loads, structural systems, materials, connections between materials and surrounding structures, etc. Despite the great relevance of laboratory experimental tests, where specimen testing is done in controlled environments as required to develop and calibrate numerical models, *in-situ* tests also play a major role in order to use such calibrated models and to adjust them to real conditions, thus finally allowing assessing the behavior of existing structures. Indeed, as shown below, it is possible to carry out low cost experimental tests with significant data outcome to study elements/structures' behavior.
Moreover the continuous monitoring of new/existing structures is increasing due to the invaluable data they can provide over time, quite relevant to understand the evolution of structures' performance and to allow repairing/strengthening/retrofitting on due time.

References

[1] M. Tomazevic, Earthquake-resistant design of masonry buildings, *Imperial College Press*, 1999.

[2] A.A. Costa, Experimental Testing of Lateral Capacity of Masonry Piers, An Application to Seismic Assessment of AAC Masonry Buildings, MSc Thesis on Earthquake Engineering, *European School for Advanced Studies in Reduction of Seismic Risk (ROSE School)*, Pavia, Italy, 2007.

[3] M.C. Griffith, J. Vaculik, N.T.K. Lam, J. Wilson and E. Lumantarna, "Cyclic testing of unreinforced masonry walls in two-way bending," *Journal of Earthquake Engineering and Structural Dynamics*, Vol.36, No.6, 801-821, 2007.

[4] A.S. Mosallam, "Out-of-plane flexural behavior of unreinforced red brick walls strengthened with FRP composites," *International Journal of Composites Part B:Engineering*, Vol.38, 559-574, 2007.

[5] G. Milani, F.A. Zuccarello, R.S. Olivito and A. Tralli, "Heterogeneous upper-bound finite element limit analysis of masonry walls out-of-plane loaded," *Journal of Computational Mechanics*, Vol.40, No.6, 911-931, 2007.

[6] A. Costa, "Determination of mechanical properties of traditional masonry walls in dwellings of Faial Island, Azores," *Journal of Earthquake Engineering & Structural Dynamics*. Vol.31, No.7, 1361 – 1382, 2002.

[7] A. Arêde, A. Costa, A.A. Costa, C.S. Oliveira and F. Neves, "Caracterização Experimental do Sistema Construtivo do Grupo Central do Arquipélago Açoreano – Uma Contribuição para a Avaliação e Redução da sua Vulnerabilidade Sísmica," *SÍSMICA 2007 – 7º Congresso de Sismologia e Engenharia Sísmica*, FEUP, Porto, 2007 (in Portuguese)

[8] A.A. Costa, A. Costa, A. Arêde, C.S. Oliveira and F. Neves, "Metodologia da preparação de ensaios a realizar na ilha do Faial, Açores," *SÍSMICA 2007 – 7º Congresso de Sismologia e Engenharia Sísmica*, FEUP, Porto, 2007 (in Portuguese).

[9] C. Costa, Análise do Comportamento da Ponte da Lagoncinha sob a Acção do Tráfego Rodoviário. MSc Thesis on Civil Engineering, Faculdade de Engenharia da Universidade do Porto (FEUP), 2002 (in Portuguese).

[10] L.A. Ferreira, F.M. Araújo, A.A. Maia, P.A. Alves and J.L. Santos, "Redes de Bragg em Fibra Óptica - Contribuições para o desenvolvimento de uma tecnologia revolucionária em monitorização estrutural", Betão Estrutural 2004, 1031-1038, FEUP, Porto, 2004.

[11] Geokon, Inc., *Earth Pressure Cells* , 2002.

[12] A. Arêde, P. Costa, A. Costa, C. Costa and L. Noites, "Monitoring and testing of a new stone masonry arch bridge in Vila Fria, Portugal," *Proceedings of Arch'07*, Funchal, 2007.

[13] P. Costa, Análise da Construção e do Comportamento de uma Ponte de Pedra, MSc thesis on Civil Engineeering, *Faculdade de Engenharia da Universidade do Porto (FEUP)*, 2007 (in Portuguese).

[14] P. Pasquet, "Manuel d'utilisation de Cast3m," www-cast3m.cea.fr. Commissariat à l'Énergie Atomique, 2003.

[15] C. Costa, P. Costa, A. Arêde and A. Costa, "Structural design, modelling, material testing and construction of a new stone masonry arch bridge in Vila Fria, Portugal," *Proceedings of Arch'07*, Funchal, 2007.